The WRP Notebook

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Engineering Description of Wetland Soils

PURPOSE: This technical note provides guidance for describing soils as part of the site evaluation and soil survey as an aid to identify wetland soils, to delineate wetland areas, and to determine construction properties required for wetland engineering. It provides guidance on how to describe wetland soils by field expedient and laboratory procedures. A field expedient description is useful to obtain a preliminary identification of soils and to determine preliminary engineering properties. Laboratory procedures accurately identify the soils and provide the best evaluation of engineering properties from soil description data. Evaluation of engineering properties is not within the scope of this technical note. The information supplements the design sequence contained in WRP Technical Note WG-RS-3.1.

BACKGROUND: Wetland soils typically include hydric sediments with an organic component of decomposed plant material (peats and mucks). A hydric soil contains abundant moisture and under wetland conditions will periodically be in a reduced state containing limited oxygen and a high water table. Sediments are materials that are deposited or settle to the soil surface from an overlying body of water. The organic material can influence soil parameters. Organic soils are readily identified by their color, odor, spongy feel and frequently by a fibrous texture.

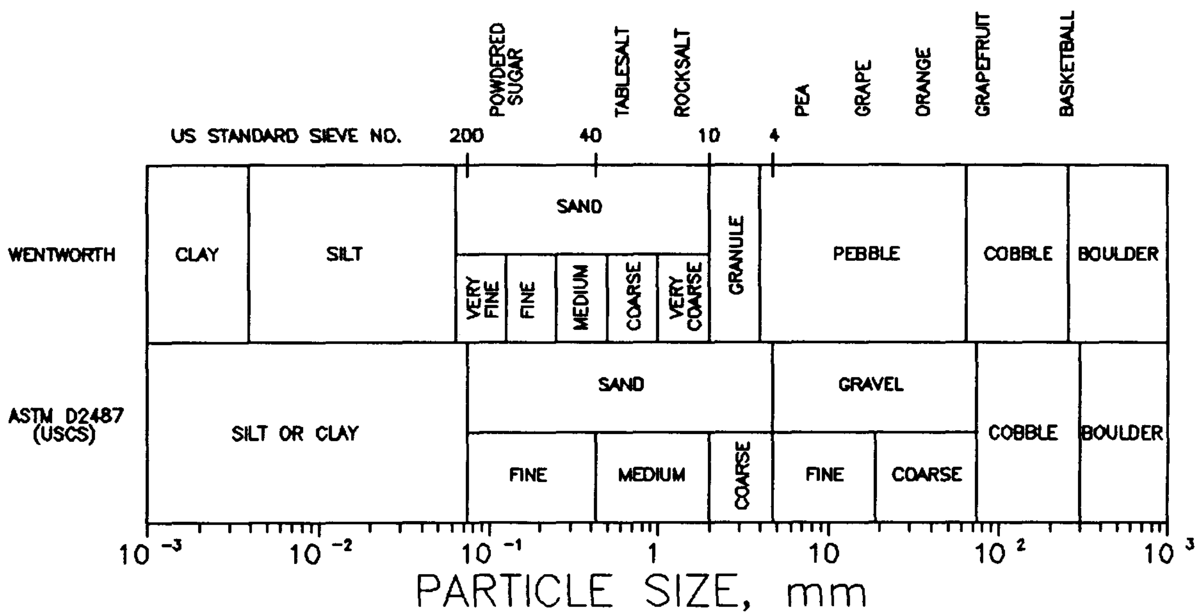
Diagnostic horizons of wetland soils include primitive entisols (E1), young inceptisols (I2), and mollisols (M1). Entisols (E1) are weakly developed wet soils with only A (exposed soil surface) and C (underlying parent material) horizons. The A horizon is young because of material deposited by water or some other agent. The A horizon will probably be a black, thick, fertile (mollic) or less fertile (umbric) soil. Inceptisols (I2) are usually moist immature soils commonly found in depressions where soil development is slowed by lack of periodic drying. Mollisols (M1) are found under wet grasslands with dense, fibrous root systems leading to a thick, dark, humus-enriched A horizon.

The thrust of the engineering description should be to identify soil from the texture; i.e., relative size, shape, and hardness of soil particles. The soil description with some information on mass (density, void ratio, water content) properties is sufficient to estimate a typical range of in situ or compacted soil properties for engineering applications.

Wetland soils are often sands with silts and clays. Particle sizes will typically be less than 4.75 mm (No. 4 US Sieve), according to the Wentworth (Müller 1967) or ASTM D 2487 (Unified Soil Classification System, USCS), Table 1. Table 2 identifies soil in terms of group symbols and typical group names by a field expedient procedure that uses the USCS. Soils possessing characteristics of two groups are designated by combinations of group symbols. For example, a GW-GC soil is a well-graded gravel-sand mixture with clay binder. A wetland soil may contain some sands with group symbols SW, SP, SM, and SC and may also contain silts and clays with group symbols ML, CL, OL, MH, CH, OL, and even may contain PT. A wetland soil will usually not contain any gravels.

Soft, compressible, fine-grained soil such as organic silt (OL), organic clay (OH), normally consolidated plastic clay (CH), peat (PT) or muck are undesirable for supporting embankments, roads, or other structures. Lean clays (CL) with plasticity index PI $\leq$ 12 and liquid limit LL $\leq$ 35, sands

Table 1. Grain Size Classification of Soils



(SC, SM-SC, SM, SP, SW), and gravels (GW, GP, GM, GC) usually provide the best soils for construction. Disturbed soil samples are required for an engineering description. Surface soils may be readily obtained by digging a small test pit with a pick and shovel or excavating a large test pit or trench with a backhoe, scoop, clamshell bucket or other mechanical equipment. Subsurface soil samples may be obtained by hand or machine-operated augers, piston, and other samplers (EM 1110-2-1907).

FIELD EXPEDIENT DESCRIPTION: An approximate description of wetland soils may be made in the field by observation and tests with portable equipment to determine the parameters given below. Equipment required to complete a field expedient description of soils is given in Table 3.

- Acid test. This test can determine the presence of calcium carbonate in the soil. Calcium carbonate is normally desirable because of the cementing action it provides and the soil strength that can be added to compacted soil over time. This test permits a better understanding of abnormally high strength values of fine-grained soils that are tested in-place. The test is conducted by placing a few drops of hydrochloric acid on a piece of the soil. A fizzing reaction (effervescence) indicates the presence of calcium carbonate.

- Bite test. This test is useful for identifying sand, silt, or clay. Sands grate harshly between the teeth, while silts feel gritty. Clays are not gritty, but feel smooth and powdery like flour.

- Breaking test. A pat of minus No. 40 sieve fraction is molded to 13 mm (1/2 in.) thickness by 32 mm (1-1/4 in.) diameter in the wet plastic state and allowed to dry completely. An attempt to break the thoroughly dried pat is made by using the thumb and forefingers of both hands. Avoid breaks along shrinkage cracks because these will not indicate the true breaking strength. The soil is roughly described as follows:

Table 2. Field Expedient Soil Classification (Data from Table 2-1 of FM 5-541, "Military Soils Engineering)

Major Divisions	Minor Divisions	Group Symbol	Typical Group Names and Description
Coarse-grained: Particles less than 75 mm (3 in.) and more than half larger than No. 200 sieve	Gravels: More than half larger than No. 4 sieve	GW	Well-graded gravels, gravel-sand mixtures; wide range of sizes with few or no particles less than No. 200 sieve
		GP	Poorly graded gravels or gravel-sand mixtures; predominantly one size with few or no particles less than No. 200 sieve
		GM	Silty gravels, gravel-sand-silt mixtures; nonplastic particles less than No. 200 sieve (see ML below)
		GC	Clayey gravels, gravel-sand-clay mixtures; plastic particles less than No. 200 sieve (see CL below)
	Sands: More than half smaller than No. 4 sieve	SW	Well-graded sands, gravelly sands; wide range of sizes with few or no particles less than No. 200 sieve
		SP	Poorly graded sands or gravelly sands; predominantly one size with few or no particles less than No. 200 sieve
		SM	Silty sands, sand-silt mixtures; nonplastic particles less than No. 200 sieve (see ML below)
		SC	Clayey sands, sand-clay mixtures; plastic particles less than No. 200 sieve (see CL below)
Fine-grained: Particles less than No. 40 sieve and more than half smaller than No. 200 sieve	Silts and Clays: liquid limit less than 50 percent	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity; none to slight dry strength; quick to slow dilatancy, no toughness
		CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays; medium to high dry strength, none to very slow dilatancy, medium toughness
		OL	Organic silts and organic silty clays of low plasticity; slight to medium dry strength, slow dilatancy, slight toughness
	Silts and Clays: liquid limit less than 50 percent	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts; slight to medium dry strength, slow to no dilatancy, slight toughness
		CH	Inorganic clays of high plasticity, fat clays; high to very high dry strength, no dilatancy, high toughness
		OH	Organic clays of medium to high plasticity, organic silts; medium to high dry strength, none to very slow dilatancy, slight to medium toughness
Highly Organic		PT	Peat and other highly organic soils; readily identified by color, odor, spongy feel and frequently by a fibrous texture

* See text for definitions of dry strength, dilatancy, and toughness.

Table 3. Equipment for Field Expedient Soil Classification	
Equipment	**Remarks**
No. 40 U.S. standard sieve and, if available, No. 4 and No. 200 sieves	The breaking, dilatancy, dry strength, ribbon, roll, and toughness tests are performed on material passing the No 40. U.S. standard sieve. Any screen with about 40 openings per lineal inch is useful. A No. 4 sieve is useful for separating gravel and a No. 200 sieve is useful for separating fines.
Pick and shovel	Entrenching tools are required for obtaining soil samples. A hand auger should be available for obtaining samples from depths more than a few feet below the surface.
Spoon	The spoon is used to mix water with cohesive soil and to obtain a desired consistency. The consistency desired is often like that of putty. If too dry, water must be added and if sticky, the soil should be spread out in a thin layer and allowed to lose some moisture by evaporation.
Pocket knife	A pocket knife is required for obtaining samples and trimming them to the desired size.
Small mixing bowl	Cup or other small container with a rubber-faced or wood pestle are required for pulverizing fine-grained portions of the soil.
Heavy paper	Several sheets of heavy paper are required for rolling samples.
Pan and heating element	A pan and heating element are required to dry samples for sieve analysis and to determine water content. Drying by sunlight is adequate for performing the field expedient tests and classification.
Balances or scales	Scales are required for weighing samples.

CH - Soil cannot be broken or powdered or broken with great effort, but not powdered
CL - Soil can be broken and powdered with some effort
ML, MH, or CL - Soil easily broken and readily powdered
ML or MH - Soil crumbles and powdered when picked up in the hands

- Color. The color distinguishes between different strata and assists the identification of the type of soil. Color classes are chroma and achroma with brilliance, hue, and saturation attributes. Chroma colors are reds, greens, purples, browns, and pinks. Achroma colors are black, white, and grays intermediate between black and white. Brilliance measures the difference between dark (low brilliance) and light (high brilliance) colors or grays. Hue measures the difference between separate colors. Saturation measures the degree of vividness of the hue or the difference from gray. High brilliance light gray, olive green, brown, red, yellow, and white are generally associated with inorganic soils. Red, yellow, and yellowish brown colors may be caused by iron oxides. White to pinkish colors may indicate silica, calcium carbonate, or aluminum compounds. Gray, brown, and black colors indicate organic, fine-grained colloidal (OL, OH) soils. Grayish blue, gray, and yellow mottled colors indicate poor drainage. Wetland soils in a reduced state typically have a dark, gray, mottled appearance with 2 or less chroma colors.

- Dilatancy. A pat of the minus No. 40 sieve fraction of moist soil is prepared with a volume of about 8.2 cc or 1/2 cu in. Add enough water, if necessary, to make the consistency of the soil soft or like a putty, but not sticky. Place the pat in the open palm of one hand and shake horizontally, striking vigorously against the other hand several times. A positive reaction consists of the appearance of water on the surface of the pat which changes to a livery consistency and becomes glossy. When the sample is squeezed between the fingers, the water and gloss disappear from the surface, the pat stiffens, and finally it cracks or crumbles. The rapidity of the appearance of water during shaking and of its disappearance during squeezing assist in identifying the character of the fines in the soil. Very fine clean sands give the quickest and most distinct reaction whereas a plastic clay has no reaction. Inorganic silts, such as a typical rock flour, show a moderately quick reaction.

- Geophysical tests. Geophysical exploration by seismic, electrical, magnetic, and gravity methods is useful during the site evaluation to assist with identification of the soil profile and the location and thickness of the various strata. These tests allow rapid coverage of large areas at a much smaller cost than conventional equipment. Electrical and magnetic methods are influenced by salinity of the water and could reduce their usefulness in coastal wetlands. Definite interpretation of the results is often uncertain and should be applied only with other subsurface exploration (Das 1984, Telford, et al 1988).

- Grain shape. The grain shape influences soil stability. Irregular, angular particles increase frictional resistance to displacements from applied loads compared with rounded particles. Irregular particles also cause interlocking between grains to increase frictional resistance and strength.

- Odor. Sense of smell or fragrance. The odor may be increased by heating the soil sample over an open flame. Organic OH and OL soils have a distinctive, musty, slightly offensive odor. A rotten egg odor is an indicator of a hydric soil and a wetland.

- Ribbon test. A pat of the minus No. 40 sieve fraction of soil is molded to the consistency of putty without being sticky, adding water or drying if necessary. The soil is rolled by hand on the heavy paper to about 13 to 19 mm (1/2 to 3/4 in.) diameter and about 8 to 13 cm (3 to 5 in.) long. The material is placed in the palm of the hand and starting with one end, the roll is flattened to form a ribbon 6 to 13 mm (1/4 to 1/2 in.) thick by squeezing it between the thumb and forefinger. The soil should be handled carefully to form the maximum length of ribbon that can be supported by the cohesive properties of the soil. If the soil holds together for a length of 20 to 25 cm (8 to 10 in.) without breaking, the material is of high plasticity (CH).

- Roll test. A pat of the minus No. 40 sieve fraction of soil is molded to the consistency of putty without being sticky, adding water or drying if necessary. The sample is rolled rapidly into a thread 3 mm (1/8 in.) in diameter. Materials which cannot be rolled into this thread at any water content are nonplastic or of low plasticity (ML or MH). If the soil can be rolled into a thread, then the degree of plasticity is determined as follows:

  CH - Soil may be remolded into a ball and the ball deforms under extreme pressure by the fingers without cracking or crumbling.
  CL - Soil may be remolded into a ball, but the ball will crack and easily crumble under finger pressure.
  CL, ML, or MH - Soil cannot be lumped together into a ball without completely breaking up.
  OL or OH - Soils containing organic materials or mica particles will form soft spongy threads or balls when remolded.

- Slaking test. This test assists in determining the quality of shales and other soft rocklike materials. The material is placed in the sun or in an oven to dry, and then allowed to soak in water for at least 24 hours. Materials that slake appreciably are undesirable for construction.

- Toughness test. A pat of the minus No. 40 sieve fraction of soil is prepared with a volume of about 13 mm (1/2 in.) on a side and molded to the consistency of putty without being sticky, adding water or drying if necessary. Then the specimen is rolled out by hand on a smooth surface or between the palms into a thread about 3 mm (1/8 in.) diameter. The thread is then folded and rerolled repeatedly. During this manipulation the water content is gradually reduced and the specimen stiffens, finally loses its plasticity, and crumbles when the plastic limit is reached. After the thread crumbles, the pieces should be lumped together and a slight kneading action continued until the lump crumbles. The tougher the thread near the plastic limit and the stiffer the lump when it finally crumbles, the more potent is the colloidal clay fraction in the soil. Weakness of the thread at the plastic limit and quick loss of coherence of the lump below the plastic limit indicate either inorganic clay of low plasticity, or materials such as kaolin-type clays and organic clays which occur below the A-line of the plasticity chart (see FM 5-541 or ASTM D 2487). Highly organic clays have a very weak and spongy feel at the plastic limit.

LABORATORY DESCRIPTION: A precise description of wetland soils may be accomplished by the USCS. USCS is a precise system for classifying mineral and organo-mineral soils for engineering purposes based on laboratory determination of Atterberg limits and particle-size distribution. The ASTM version of the USCS is given as standard test method D 2487. Knowledge-based computer systems such as CLASS-92 (Bakeer 1992) expedite an efficient engineering description by the USCS. CLASS (Morse and Bakeer 1990) may be used to convert between Visual, USCS, ASTM, and AASHTO systems. Liquid limit, plasticity index, and the particle size distribution are sufficient to describe soil by the USCS.

- Atterberg limits. Indices expressed in terms of the water content (w) of soil in percent that are useful for general characterization of soil, particularly to evaluate the degree of plasticity and compressibility:

  Liquid limit LL, percent - water content between the liquid and plastic state. LL may be determined by ASTM D 4318.

  Plastic limit PL, percent - water content between the plastic and semisolid state. PL may be determined by ASTM D 4318.

  Plasticity index PI, percent - difference in water content between the liquid limit and plastic limit, PI = LL - PL.

- Particle size distribution - determines the proportions by mass of a soil or fragmented rock in specified ranges of particle sizes. D_n is the diameter of soil particles that is (n) percent finer by weight; e.g., D_{10} is the particle diameter at which 10 percent of the material is finer by weight. Particle size distribution may be determined by standard test method ASTM D 422. Refer to ASTM D 2487 for other methods of gradation analysis. The following gradation ratios are also applied by the USCS to classify soil:

  Coefficient of curvature C_c - $(D_{30})^2/(D_{10} \cdot D_{60})$.

  Coefficient of uniformity C_u - D_{60}/D_{10}.

Soils with C_c between 1 and 3 and C_u greater than 4 are well-graded clean gravels, GW, provided that the fines smaller than No. 200 mesh are less than 5 percent by weight. Soils with C_c between 1 and 3 and C_u greater than 6 are well-graded clean sands, SW, provided that fines smaller than No. 200 mesh are less than 5 percent by weight.

- Liquidity index LI, percent. Ratio of water content (w) minus PL to PI, (w - PL)/PI. LI close to and exceeding unity indicate normally consolidated soils, recently deposited sediments, and a potential of being wetland soils. LI exceeding unity indicates soil on the verge of being a viscous liquid. LI close to or less than zero indicates overconsolidated, desiccated soil and soil with high foundation strength.

- Shrinkage limit SL, percent. Component of Atterberg limits that is the water content between the solid and semisolid state; least water content at which the degree of saturation is 100 percent. SL may be determined by Appendix IIIB of EM 1110-2-1906. Water content near or less than SL indicates an overconsolidated, desiccated soil.

- Specific gravity of solids G_s. Ratio of mass (grams or g) in air of a given volume of solids at a stated temperature to the mass in air of an equal volume of distilled water at the same temperature. $G_s = \gamma_s/\gamma_w$, where γ_s = ratio of the solid mass to the volume of the solid mass, g/cc, γ_w = unit mass of water at 4°C, 1 g/cc. G_s may be determined by standard test method ASTM D 854. Estimates of G_s are given in Table 4. Typical G_s is 2.67 for sands and 2.70 for clays. Smaller G_s indicates soils with more organic material.

Table 4. Specific Gravities of Some Soils (After Bowles 1988)

Soil Type	Specific Gravity G_s
Sand	2.65 - 2.68
Silty sand	2.67 - 2.70
Inorganic clay	2.68 - 2.75
Inorganic silt	2.62 - 2.68
Soils with micas and iron	2.75 - 3.00
Organic clay	2.58 - 2.65

The specific gravity is used to determine mass properties such as the density, void ratio, and degree of saturation.

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POINT OF CONTACT FOR ADDITIONAL INFORMATION: Mr. Roy Leach, U.S. Army Engineer Waterways Experiment Station, ATTN: CEWES-GS-S, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, phone: (601) 634-2727, co-author.

Dr. Lawrence D. Johnson, U.S. Army Engineer Waterways Experiment Station, author.

Engineering Properties of Wetland Soils

PURPOSE: This technical note provides guidance for evaluating the engineering properties of wetland soils required for wetland engineering. Mass properties are also included to complete evaluation of the engineering properties. Engineering of wetland soils includes development and application of efficient procedures for the design, establishment and construction, restoration, operation, and maintenance of wetlands. This information supplements material outlined in WRP Technical Note WG-RS-3.1.

BACKGROUND: Engineering properties are strength, compressibility, and permeability. These properties influence the critical soil processes that govern the performance of a wetland when a force is applied to the soil.

Critical soil processes include the compaction characteristics of fill materials used to construct dikes, slope stability, and settlement of earth dikes containing water and soils in wetlands; compaction characteristics of wetland soils, sedimentation, and erosion characteristics of wetland soils, and the flow of water through wetlands and dikes. These processes influence water and sediment storage capacity, water quality and flow, and erosion from and collection of sediments on the surface of submerged wetland soils. The strategy for determining procedures for construction or restoration, operation, and maintenance of wetlands is based on the critical soil processes evaluated from the engineering properties of wetland soils.

Preliminary or approximate engineering properties of wetland soils may be evaluated from classification data with some information on mass properties such as density, void ratio, and water content. The engineering classification of wetland soils may be determined by field expedient and laboratory procedures given in WRP Technical Note SG-RS-1.1, *Engineering Description of Wetland Soils.*

Information required to determine engineering properties for final design, restoration, construction, and maintenance of wetlands may be provided from results of detailed site evaluation and soil survey. The survey should include in-situ soil tests such as cone penetration (CPT) and standard penetration (SPT) and laboratory tests performed on undisturbed soil samples. Hand-operated piston, Shelby push tubes, rotary, and samplers are available for retrieving disturbed and undisturbed soil samples as outlined in EM 1110-2-1907.

IDENTIFICATION OF MASS PROPERTIES: Mass properties are the density, void ratio, and water content of the soil.

- Density, g/cc. Mass per unit volume of material:

  Wet density γ - in-place total mass per unit total volume of material. γ may be determined by ASTM D1556, D2167, or portable field methods given in Appendix E of EM 1110-2-1907.

  Dry density γ_d - mass of solid particles per total volume of material. γ_d may be determined from $\gamma/(1 + w/100)$ where "w" is the water content on a dry weight basis in percent.

Saturation density γ_{sat} - wet density at which the pore water pressure of a normally consolidated undisturbed soil is zero. γ_{sat} of a freshly deposited (normally consolidated) sediment may be estimated by $(G_s + e_{SL})\gamma_w/(1 + e_{SL})$ where e_{SL} = void ratio at the saturation limit, $\approx 1.0 + 0.0589PI$. $\gamma/\gamma_{sat} < 1.3$ indicates possible wetland soils. γ_w = unit mass of water, 1 g/cc. G_s = specific gravity of solids.

- Dessication limit e_{DL}. Least void ratio of soil caused by desiccation. $e_{DL} \approx 1.6 + 0.0106PI$ and it occurs approximately at a degree of saturation of 60 percent. Void ratios near e_{DL} indicate an overconsolidated, desiccated soil.

- Liquidity index LI, percent. Ratio of water content w minus PL to PI, (w - PL)/PI. LI close to and exceeding unity indicate normally consolidated soils, recently deposited sediments, and a potential of being wetland soils. LI exceeding unity indicates soil on the verge of being a viscous liquid. LI close to or less than zero indicates overconsolidated, desiccated soil and soil with high foundation strength.

- Void Ratio, e. Ratio of the volume of void space to the volume of solid particles in a given soil mass. $e = (G_s/\gamma_d)\gamma_w - 1.0$ where G_s = specific gravity, γ_d = dry density, g/cc, and γ_w = unit mass of water, 1 g/cc.

- Water content w, percent. Ratio of the mass of water contained in the pore spaces of soil to the mass of solid dry material expressed as a percentage. Soil water content may be evaluated in the laboratory by ASTM D2216 or microwave oven method D4643. The natural water content of in situ soil can indicate drainage characteristics and nearness to a water table. The optimum water content of compacted fill materials allows compaction to the greatest density and strength.

  Field expedient natural water content test. A piece of undisturbed soil is tested by squeezing it between the thumb and forefinger to determine its consistency; i.e., hard, stiff, brittle, friable, sticky, plastic or soft. The soil is then remolded by working it in the hands, and changes, if any, are observed. Clays which turn almost liquid on remolding are probably near or above the liquid limit. If the clay remains stiff and crumbles upon being remolded, the natural water content is below the plastic limit.

  Field expedient optimum water content (OMC) test. A golf ball size of soil is molded by hand and squeezed between the thumb and forefinger. If the ball shatters into several fragments of rather uniform size, the soil is near or at OMC. If the ball flattens out without breaking, the soil is wet of the OMC. If the soil is difficult to roll into a ball or crumbles under very little pressure, the soil is dry of the OMC.

IDENTIFICATION OF ENGINEERING PROPERTIES: Engineering properties are the strength, compressibility, and permeability parameters of the soil.

- Strength properties. Strength parameters define the ability of soil to support dikes, retaining walls, pavements, and other structures and to resist erosion from flowing water. The shear strength τ is given by Coulomb's equation in terms of strength parameters c and ϕ, $\tau = c + \sigma_n \tan\phi$ where σ_n is the component of stress normal to the shear plane. The shear stress τ is tangent to the shear plane.

c, cohesion, kPa - shear resistance at zero normal stress or the intrinsic shear strength. A perfectly cohesive soil has strength only from cohesion where $\phi = 0$. The shear strength of a clay when undrained is $c = C_u$ where C_u is the undrained shear strength. The compressive strength q_u is twice the undrained shear strength. q_u is usually determined on specimens not confined by any applied stress.

ϕ, friction angle, degrees - The angle of internal friction or angle of shear resistance is the angle between the axis of normal stress σ_n and tangent to the mohr envelope at a point representing a given failure stress condition for the soil. A perfectly cohesionless soil or sand has strength only from friction where $c = 0$.

- Compressibility properties. These properties include both elastic and consolidation parameters. Elastic parameters define the ability of soil to resist elastic deformation and settlement from applied forces. Elastic deformation occurs almost immediately and accounts for nearly all or most of the settlement in cohesionless soil. Consolidation parameters define the ability of saturated soil to resist settlement or heave caused by applied forces. Changes in applied forces instantly cause corresponding changes in pore water pressure leading to the flow of water into or out of the soil. The resulting consolidation from changes in the water content occurs over time depending on the ability of the soil to conduct water (permeability properties). Consolidation in cohesive soil occurs over a relatively long time and often accounts for most of the settlement.

E, modulus of elasticity, kPa - This elastic modulus of deformation is the ratio of stress to strain for a soil under given loading conditions. E is often used to determine immediate settlement from static loads.

G, shear modulus, kPa - the shear moduus is the ratio of shear stress to shear strain under given loading conditions. G is often used to determine deformation or settlement from dynamic loads or vibrations. G is related to E by Poisson's ratio ν, $G = E/[2(1 + \nu)]$. Poisson's ratio is the ratio between linear strain changes perpendicular to and in the direction of a given uniaxial stress change.

C_c, compression index - The compression index is the slope of the linear portion of the pressure-void ratio curve on a semi-log plot. The linear portion occurs at pressures exceeding the maximum p[ast pressure σ_p that had been applied to the soil.

C_r, recompression index - The recompression index is the slope of the pressure-void ratio curve on a semi-log plot following removal of the maximum pressure σ_p that had been applied to the soil, but at pressures that exceed the vertical overburden pressure σ_v that was applied to the in situ soil.

Overconsolidation ratio OCR. The OCR is the ratio of preconsolidation pressure σ_p' to the effective overburden pressure σ_v'. $\sigma_v' = \sigma_v - u_w$, σ_v = total overburden pressure, u_w = pore water pressure, kPa. OCR of a normally consolidated soil is unity. OCR of overconsolidated soil exceeds unity. Wetland soils are often normally consolidated.

- Permeability Properties. Permeability is a property of a mass soil that controls the rate of flow of water Q through the soil. Permeability is influenced by the void ratio, continuity of voids, and fissures that may be caused by drying and wetting weather cycles.

k, coefficient of permeability, cm/sec - The permeability controls the flow of water Q through a cross-section area A of soil depending on the hydraulic gradient i, k = Q/(iA). The hydraulic gradient is Δh/L where Δh is the difference in height of the water columns in a standpipe inserted at the entrance end and at the exit end of a filter bed and L is the length of the filter bed between the standpipes.

c_v, coefficient of consolidation, cm^2/sec - c_v is used in the Terzaghi theory of consolidation containing the physical constants of a soil affecting its rate of volume change,

$$c_v = \frac{k\,(1 + e)}{\gamma_w a_v}$$

where e = void ratio, γ_w = unit weight of water, 1 g/cc, a_v = coefficient of compressibility, cm^2/g.

EVALUATION OF ENGINEERING PROPERTIES: Engineering properties may be approximated from classification data or evaluated from in situ and laboratory soil tests.

- Strength parameters. Angle of internal friction ϕ, deg. Angle between the normal stress axis and tangent to the Mohr envelope at a point representing a given failure stress of the soil. ϕ is required to evaluate the slope stability and bearing capacity of cohesionless soil or sands. ϕ is usually estimated from correlations of field soil tests such as cone penetration (CPT) or standard penetration (SPT) tests because undisturbed boring samples for laboratory tests are rarely obtainable for sands. Table 3-1 in EM 1110-1-1905 provides correlations of ϕ with relative density, CPT (ASTM D 3441), and SPT (ASTM D 1586). Figure 1 correlates the soil classification and the dry unit weight γ_d with ϕ when CPT or SPT data are not available.

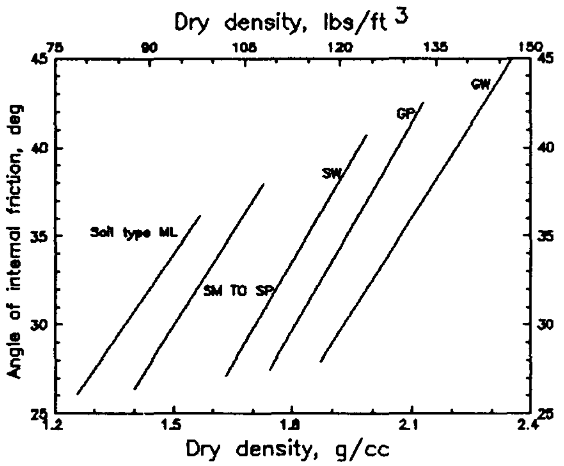

Figure 1. Strength characteristics for cohesionless soils

Unconfined compressive strength q_u, kPa. Strength at which an unconfined cylindrical specimen of soil will fail in a simple compression test. A simple portable field device for estimating q_u, the pocket penetrometer, is a small, hand-operated, spring-calibrated penetrometer for estimating the engineering consistency of cohesive, fine-grained soils, Table 1. This device is pushed into soil surfaces and it is calibrated to determine q_u in kilograms per square centimeter (1 kg/cm^2 = 100 kPa). The apparatus and procedure are described by Bradford (1986). Clays of medium or softer consistency are normally consolidated and may be in wetlands. Stiff and harder clays are overconsolidated.

Vane torque T_v, N·m. The turning moment required to shear a cylindrical column of cohesive soil. The torque may be determined by a four-bladed vane device according to standard test method ASTM D 2573.

Undrained shear strength C_u, kPa. The maximum resistance to shear forces when pore pressures are not drained. C_u is required to evaluate slope stability and bearing capacity of cohesive soils. C_u may be estimated from results of the pocket penetrometer test as 1/2 of q_u, the unconfined compressive strength. C_u may also be estimated from results of the field vane shear test by T_v/K_v where K_v is the vane constant. K_v depends on dimensions and shape of the vane (ASTM D 2573).

- Compressibility properties.

Compression index C_c. Slope of the linear portion of the pressure-void ratio curve on a semi-log plot. This parameter is required to evaluate settlement caused by consolidation of compressible soil. C_c may be estimated by -0.156 + 0.411e + 0.00058LL (Al-Khafaji and Andersland 1992) where the correlation coefficient is 0.957 and standard error is 0.077 based on 72 data points. Refer to EM 1110-1-1904 for other correlations.

Elastic Young's modulus E_s, kPa. Ratio of vertical stress σ_v to the vertical strain caused by σ_v. E_s is used to estimate elastic settlement of soils according to procedures given in EM 1110-1-1904. E_s may be estimated from a general classification given in Table 2.

Table 1. Correlation of Consistency With Shear Strength of Cohesive Soil

Relative Consistency	Unconfined Compressive Strength q_u, kPa
Fluid mud	< 2
Very soft	2-25
Soft	25-50
Medium	50-100
Stiff	100-200

Table 2. Typical Elastic Moduli

Soil	E_s, kPa
Clay	
Very soft	500 - 5,000
Soft	5,000 - 20,000
Medium	20,000 - 50,000
Stiff, silty	50,000 - 100,000
Sandy	25,000 - 200,000
Shale	100,000 - 200,000
Sand	
Loose	10,000 - 25,000
Dense	25,000 - 100,000
Dense w/gravel	100,000 - 200,000
Silty	25,000 - 200,000

- Permeability properties.

Coefficient of permeability k, cm/sec. Rate of discharge of water under laminar flow through a unit area of a porous medium for a unit hydraulic gradient at a standard temperature, usually 20°C. k is required to evaluate the quantity and rate of fluid flow through soils. k is given from classification data by Table 3. k may be estimated by Figure 2 for sands from gradation data and void ratio e. k may be estimated for clays from $0.1C_v\gamma_w m_v$ where C_v = coefficient of consolidation, cm^2/sec, γ_w = unit mass of water, and m_v = coefficient of volume change, kPa^{-1} (1 cm^2/g = 10 kPa^{-1}). C_v may be estimated from the liquid limit LL by Table 4. Undisturbed sediments not subject to wet/dry cycles should have C_v similar to those for virgin consolidation. Soil subject to wet/dry cycles should have C_v similar to soil subject to recompression. $m_v = 0.435C_c/[(1 + e)\sigma_{mv}]$ where C_c = compression index and σ_{mv} = mean vertical stress on the soil in the field, kPa.

Table 3. Coefficient of Permeability by Soil Classification

Soil Type	k, cm/sec
GW-SW	> 10^{-2}
GP-SP	$5 \cdot 10^{-4}$ - 10^{-2}
MP-OL	10^{-5} - $5 \cdot 10^{-4}$
GF-SF-MH	$5 \cdot 10^{-7}$ - $5 \cdot 10^{-4}$
GC-SC-CL	$5 \cdot 10^{-7}$ - 10^{-5}
CL-CH-OH	< $5 \cdot 10^{-7}$

Table 4. Correlation of Liquid Limit with the Coefficient of Consolidation. (After Lambe and Whitman 1969)

LL, Percent	C_v, cm^2/second	
	Recompression	Virgin
30	0.035	0.005
60	0.0035	0.001
100	0.0004	0.0001

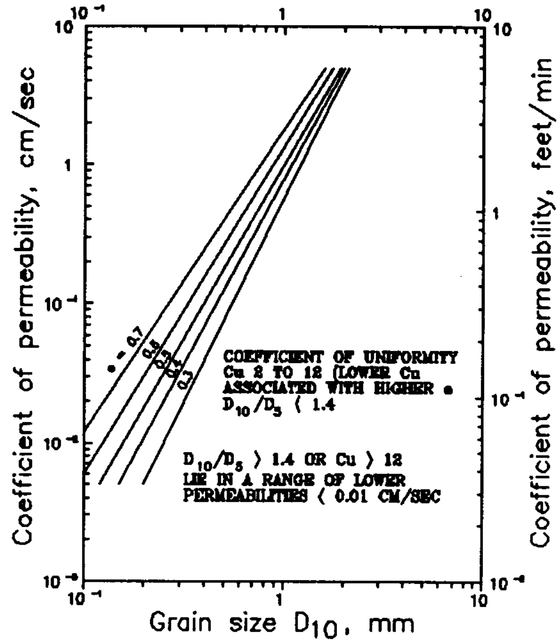

Figure 2. Permeability of sands and sand-gravel mixtures from void ratio and gradation data (After NAVFAC DM-7.1). e = void ratio; Cu = coefficient of uniformity, D_{60}/D_{10}

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POINT OF CONTACT FOR ADDITIONAL INFORMATION: Mr. Roy Leach, U.S. Army Engineer Waterways Experiment Station, ATTN: CEWES-GS-S, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, phone: (601) 634-2727, author.

Dr. Lawrence D. Johnson, U.S. Army Engineer Waterways Experiment Station, co-author.

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Soils Handling Techniques and Equipment for Wetlands Restoration and Establishment

PURPOSE: This technical note provides guidance on soils handling methods and equipment needed if earthwork, i.e., excavation and/or fill, is required for the establishment or restoration of a wetland. It supplements the information available from other WES programs and is an extension of the soils handling requirements of the design sequence contained in WRP Technical Note WG-RS-3.1 (USAEWES 1992). Emphasis is placed on criteria for selecting suitable soils handling equipment and methods.

BACKGROUND: If the substrate, size, depth and/or shape of a wetland being restored or established is unsuitable, soils handling may be necessary to: (1) excavate upland soils down to wetland elevation, (2) place fill material to raise the submerged bottom up to wetland elevation, and/or (3) to place fill in dikes to retain water. Soils handling methods developed at WES are based on lessons learned in programs dealing with soft soils such as the Dredged Material Research Program (DMRP) (Willoughby 1978), the Dredging Research Program (DRP), and the Environmental Effects of Dredging Program (EEDP).

USE OF CONSISTENT TERMINOLOGY: Because of the diverse backgrounds of persons describing and classifying soils for a wetland project, it is vital that consistent terminology and classification methods be understood and used. The U.S. Army Corps of Engineers describes and classifies soils by the Unified Soil Classification System (USCS). This system (Casagrande 1948, USAEWES 1953, ASTM 1992) uses gradation and Atterberg limits to rate soils for use in airfield base courses. Corps geotechnical engineers also use the USCS for general soil description. The USCS is a disturbed soil material-based descriptor system and descriptions must be supplemented with additional terms to describe other important material descriptors and the dynamic behavior properties of the in-situ soil. When describing the shear strength of soils, the following terms are generally used:

Relative Consistency of Cohesive Soils	Relative Compactness of Cohesionless Soils
Fluid	Very Loose
Very Soft	Loose
Soft	Medium Dense
Medium Soft	Dense
Stiff	Very Dense
Very Stiff	
Hard	

Each of these terms is defined in terms of tests of the in-situ material except in the case of Fluid consistency. Relative consistency of cohesive (clayey) soils is based on the unconfined compressive strength test. The Fluid consistency occurs when a cylindrical test specimen of cohesive material will not stand unconfined under its own weight and, therefore, may be considered to have a negative unconfined compressive strength. Relative compactness of cohesionless (clean granular) soils is defined by the relative density and measured in the field using; (1) the Standard Penetration Test (SPT) (recording blow counts obtained while driving a sample tube into the soil), or (2) the Cone

Penetrometer Test (CPT) (recording force required to push a cone of a certain cross sectional area into the soil).

Trafficability of construction vehicles on soft soils has received considerable attention at WES in studies of dredged material containment sites in the DMRP and EEDP. Recent methods for assessing equipment mobility have been summarized by Poindexter-Rollings (1990) in Technical Note EEDP-09-5. They include work by Willoughby (1978) for modifying a model for evaluating strength variation with depth. Field data for the model are obtained by pushing a hand-held cone penetrometer into in-situ dredged/fine-grained material and a remolded sample to determine a cone index (CI) and a remolded index (RI), respectively, for the soil. The product of the CI and the RI yields the rating cone index (RCI), a measure of soil strength that can be used with a ground pressure versus RCI curve to predict the number of passes specified equipment can be expected to make on a site before soil failure. Other studies of near-surface shear strength (a rut is a bearing capacity failure of a moving footing) involve the use of a hand-held vane shear device for use in cohesive soils. Strengths obtained with the vane shear device can be correlated with bearing pressure associated with earth moving equipment.

SOIL PROPERTIES IMPORTANT TO SOILS HANDLING: The engineering behavior of a soil in earthwork (soils handling) is a function of its geotechnical properties, i.e., the properties of the soil materials, the properties of the soil mass, or the dynamic behavior properties (Spigolon 1992). All of the soil properties may be directly evaluated, or reasonably estimated, by field or laboratory tests. Trafficability of the soil and its ability to support the operation of site specific equipment is also an important property.

- Soil material properties are those of the soil components, without reference to their arrangement in the soil mass:

  -- Grain size distribution
  -- Atterberg liquid and plastic limits (reflecting the mineralogy of the grains and the amount of clay sizes)
  -- Angularity, shape, and hardness of coarse grains
  -- Grain specific gravity (needed for mass-volume calculations)
  -- Organic content; lime content; cementation
  -- Color (often useful in identifying similar soils and in correlating strata)

- Soil mass properties are those relating to the arrangement of individual particles and other components in a soil mass:

  -- In-situ density (weight per unit of volume)
  -- In-situ water content (as a percentage of dry weight of solids)
  -- In-situ structure of clayey soils (blocky, stratified, slickensided, etc.)

- Soil dynamic behavior properties are those that indicate the behavior of the soil under external force systems. They result from a specific combination of soil material and soil mass properties. A soil having specific material properties may be arranged with various mass properties, and a specific group of mass properties may be attained using soils of differing material properties. The dynamic behavior properties include:

- -- Permeability
- -- Shear strength (the consistency of cohesive soils, a product of the compactness of granular soils, degree of cementation of cemented soils, or the compressive strength of rock)
- -- Consolidation (the total volume change and time rate of compression under an external load or self weight)
- -- Adhesion/stickiness (of moist cohesive soils)
- -- Rheologic properties of a slurry (soil-water mixture), i.e., viscosity and yield stress as a function of slurry composition and density
- -- Bulking factors for redeposited soils.

SOIL HANDLING PROCESSES AND EQUIPMENT: Soil handling for a wetlands project is accomplished in three phases:

- Excavation or cut (loosening or dislodging the soil material from its in-situ location)
- Removal and Transport (movement of the soil from its in-situ location to the deposition area)
- Deposition or fill (placement and manipulation of the soil in a land fill or a land or water disposal area)

The equipment for performing this work may use either hydraulic or mechanical methods or a combination. The hydraulic methods use pumped fluid flow to create and move a soil-water slurry. The mechanical methods involve discreet, bulk units of soil that are excavated and moved without slurrying or pumping. Equipment and methods are discussed in another section.

The mechanisms involved in the earthwork construction phases are:

- Excavation (cut) Phase--(l) cutting (ripping) with a knife, blade, or plow; (2) scooping (digging) with a bucket, shovel, or clamshell; (3) scour (erosion) from a moving water or air stream; and (4) direct hydraulic suction of extremely soft or extremely loose soils into a suction pipe.
- Removal and Transport Phase--(1) mechanical, using containers such as a land based loader-scraper, truck, or conveyor belt, or water based equipment such as a barge; or (2) hydraulic, pumping a slurry of soil particles, clumps of material, or clay balls, in a pipeline.
- Deposition Phase--(1) materials are discharged from mechanical containers by direct dumping from the transport unit; and (2) the pipeline slurry is directly discharged into a land or water disposal area. Compaction may be done by mechanical rolling or, for clean granular materials, by vibration.

Trafficability of the soils handling equipment is another major factor in earthwork. Soils handling equipment must be capable of maneuvering on the ground surface environment at the project site. Ground surfaces may range from (l) fairly dry, firm upland areas, to (2) very soft surface soils in swampy areas where the free water surface is just above or just below the ground surface, to (3) extremely soft (fluid mud) to firm soils at substantial depths below water. It is expected that most wetlands earthwork will be conducted on the type (2), soft swampy soil surfaces, or with dredging equipment in an aqueous environment.

EXCAVATION PROCESSES AND EQUIPMENT: During the excavation phase, the shear strength of the in-situ soil is the dominant behavior characteristic. The cuttability, scoopability, scourability, and direct suctionability mechanisms all involve shearing the undisturbed soil. The adhesion or stickiness of moist clayey soils to steel cutting or scooping equipment contributes to shearing resistance. Shear strength, in turn, is a function of the externally applied loads (usually self-weight only) and the type of soil. During excavation, the rate of shear is extremely fast; therefore, there is little or no drainage of pore water. The shear strength of a clean granular soil, with little or no fines, is a direct function of its relative density, defined as relative compactness, and the angularity of the grains. With no drainage, the shear strength of a cohesive soil is its unconfined compressive strength, defined as relative consistency.

Equipment for mechanical excavation includes cutting devices (dozers, loader-scrapers) and scooping systems (backhoes, shovels, bucket ladder, draglines, and clamshells). Hydraulic excavation equipment includes various types of equipment for dislodging the soil for inclusion in a slurry to be removed by suction (direct suction, cutter suction, bucketwheel suction).

The suitability of an excavation device depends on the trafficability of the surface and the characteristics of the soil to be excavated. Mechanical cutting devices depend on traction from wheels or tracks for reaction to cutting forces; therefore, they are generally limited to firm surfaces. The working platform for scooping systems may vary from (1) wheels or tracks on dry, firm ground, to (2) very low pressure carriages such as pontoons or very large wheels or tracks (Willoughby 1978, Poindexter-Rollings et al. 1990) in soft swampy soils (Figures 1, 2, and 3), to (3) barges or self-propelled vessels for dredging work. Hydraulic slurry systems require large quantities of water and are generally (but not necessarily) mounted on floating platforms, such as barges or self-propelled vessels (Figure 4).

TRANSPORTATION PROCESSES AND EQUIPMENT: Once the soil has been excavated, its in-situ mass and dynamic properties are destroyed. However, the soil material properties remain unchanged and are still relevant. Water content may be less due to drying upon excavation or greater because of slurrying.

Mechanical equipment for transporting soils generally consists of containers such as loader-scrapers, wheeled trucks, conveyor belts, or barges. Trafficability of the excavation site and of haul roads will determine the necessary type and contact pressure of the hauling equipment. Hydraulic equipment generally consists of a slurry pipeline.

Soil properties affecting the transportation equipment are: bulking, pumpability, and abrasiveness. Bulking is the general increase in volume of a soil compared to its in-situ volume; this affects planning for required container volumes and measurement of production based on volume. Pipeline pumpability is a function of the median (50%) grain size (Herbich 1992); the larger the median size, the greater the pumping energy required. Abrasion of pump parts and of the pipeline depends on grain size and the angularity and hardness of coarse grains. The larger, more angular and harder the grain size, the greater the abrasion.

DEPOSITION SITE PROCESSES AND EQUIPMENT: Deposition at a fill site may be mechanical or hydraulic, depending on the transport method. If the excavated and transported soil is to be simply discarded, then mechanical dumping or hydraulic slurry placement on a land or water disposal site without manipulation is suitable. The only geotechnical concern will be the possible sticking of moist clayey soils to the container and the turbidity of the water for underwater disposal. If, however, the soil is to be graded, used for a structure, or a fill is to be made, then the amount and type of compaction to be used will determine the type of processing methods and equipment.

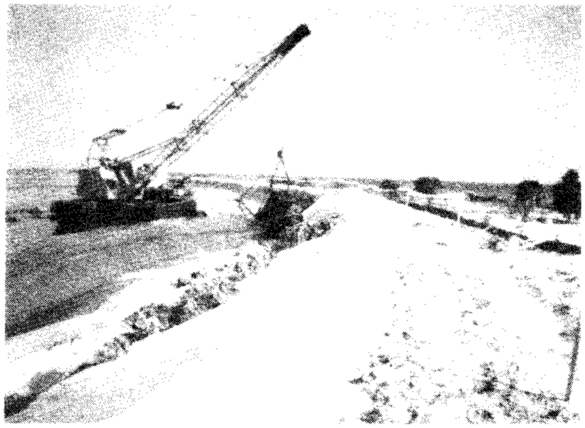

Figure 1. Quality marsh dragline

Figure 2. Bulldozer and scraper removing crust

Figure 3. Low-ground-pressure bulldozer through crust

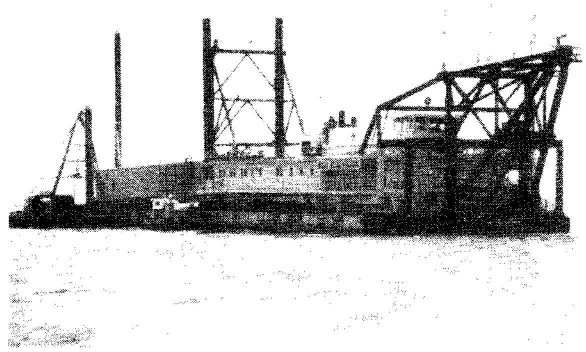

Figure 4. The Dave Blackburn dredge

There are a several methods of fill placement of soils above water level:

- Simple dumping: from the transport containers or the pipeline; minimal mechanical manipulation (grading) is used; no attempt is made at densification; excess water drains away or evaporates.
- Machine (partial) compaction: some mechanical densification (compaction) is achieved by wheels or tracks of grading machinery; no attempt is made to densify to a specification value.
- Full (specification) compaction: mechanical densification, using vibration or rollers, on thin soil layers, to achieve a specified compaction amount.

Densification methods appropriate for mechanical compaction (partial or full) depend on the soil type:

- Cohesionless (clean granular) soils: can only be densified with vibratory equipment; usually not sensitive to moisture content.
- Cohesive (clay, silty clay) and friable mixed grain soils: may only be densified using weighted rollers; vibration will not work; densification is directly dependent on water content and on the

plasticity of clay; required roller energy is directly related to water content; excess water content may prevent achievement of the desired amount of densification. "Optimum" densification occurs when the combination of water content and roller energy produce a degree of saturation in the soil of 85 to 95 percent.

SUMMARY: The suitability of various soil handling methods and equipment for use at a wetland site is determined by (1) the trafficability of the surface of the borrow area, the transport roadway, and the deposition site, (2) the quantity, location, and engineering characteristics of the soils to be moved, and (3) the location and specifications for wetland site deposition. Excavation, transportation, and deposition of a soil may be done by mechanical or hydraulic methods, or a combination of the two methods. Mechanical methods include all types of mechanical excavators and earth moving machines. Hydraulic methods typically involve forming and pumping a soil-water slurry. Virtually all soil types can be handled by either method.

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POINT OF CONTACT FOR ADDITIONAL INFORMATION: Mr. Roy Leach, U.S. Army Engineer Waterways Experiment Station, ATTN: CEWES-GS-S, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, Phone: (601) 634-2727.

Dr. S. Joseph Spigolon, SJS Corporation, 2220 No. 13th Court, Coos Bay, OR 97420 Phone: (503) 267-4371.